

# **Tropical Cyclone Structure And Motion**

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## **LONG-TERM GOALS**

To improve tropical cyclone track and intensity prediction through a research program combining high-resolution modeling and detailed observational studies to investigate physical processes by which the motion and structure of a tropical cyclone are modified.

## **OBJECTIVES**

The objective is to investigate the physical processes that occur as a tropical cyclone interacts with the environment such that motion and structure changes occur. Specific interactions being studied are with vertical wind shear environments in the tropics and with baroclinic environments in the midlatitudes during extratropical transition. During extratropical transition, radical changes to the storm structure occur as vertical wind shear and intruding cold, dry air from the midlatitudes erode the warm core. Re-intensification to a strong midlatitude system is possible. In cases in which forecast models poorly predicted the motion and re-intensification of the storm during these transitional periods, better understanding of these processes should improve motion and intensity forecasts. In addition, the processes associated with tropical cyclone formation are also studied using satellite instrumentation.

## **APPROACH**

Due to the scarcity of detailed observations in regions where tropical cyclones develop and move, high-resolution, idealized modeling is combined with observations in the studies described here. The degree of physical complexity included in current mesoscale models allows detailed examination of environmental and small-scale impacts on the motion, structure, and intensity of tropical cyclones. However, caution must be taken when applying cause and effect arguments to describe the complex physical interactions that develop in these high-resolution models since they may be a product of the model parameterizations rather than realistic physical processes. Thus, a tiered approach is employed in which understanding of basic processes comes first and is built upon by gradually adding to the complexity of the modeling system, while isolating each physical process in turn. The U.S. Navy's coupled ocean-atmosphere mesoscale prediction system (COAMPS) is the primary model used in ongoing studies into extratropical transition effects on tropical cyclone motion and structure. Where available, detailed observations such as those available from the ONR-sponsored TCM-92 and TCM-93 field experiments are used to verify processes examined in the model experiments.

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## WORK COMPLETED

Simulations using COAMPS investigated the structural changes that occur as a simulated tropical cyclone interacts with a midlatitude environment. Previous work was extended to include the interaction with an idealized upper-level trough such as might be encountered during extratropical transition. A baroclinic environment was simulated into which upper-level potential vorticity anomalies were inserted and allowed to grow. A tropical cyclone was then inserted into this environment and the structural changes that occurred as the tropical cyclone and upper-level wave interacted were examined. A journal article (Ritchie and Elsberry 2001) from the first part of this study was published in the *Monthly Weather Review*.

Simulations using MM5 investigated the structural changes that occur as a tropical cyclone interacts with vertical wind shear in the deep tropics. Work completed includes several simulations in which a mature steady-state tropical cyclone is inserted into a large-scale environment. A journal article (Frank and Ritchie 2001) from this study was published in the *Monthly Weather Review*.

A study investigating the physical processes associated with tropical cyclone genesis was also ongoing during this period. The emphasis of this study is on using satellite instrumentation that is becoming routinely available in the historically data-scarce tropical regions. To date, two cases of genesis in the Atlantic have been studied in detail using various polar orbiting satellite instruments in combination with model analyses and upper-air soundings to distinguish the mechanisms that separate developing from non-developing disturbances. A book chapter on this work (Ritchie et al. 2001) has been submitted to the American Geophysical Union for review.

## RESULTS

(1) Extratropical transition of tropical cyclones has been hypothesized to occur in two stages (Klein et al. 2000). The first stage, called transformation, occurs as a tropical cyclone encounters cooler air and waters and a baroclinic zone associated with midlatitude westerlies. Re-intensification subsequently occurs in some systems when, as part of an interaction with an upper-level trough, re-deepening of the system to a significant midlatitude storm takes place. Their rapid forward motion, high winds, and heavy precipitation make these transitioned cyclones a significant forecast problem for shipping. The Klein et al. (2000) study identified three steps in the transformation stage of extratropical transition during which the tropical cyclone interacts with different aspects of the midlatitude, baroclinic environment. The composite wind fields of the Steps 1, 2, and 3 of tropical cyclone transformation that they calculated were used as a guide to create an idealized baroclinic environment. The tropical cyclone was then located within that environment at the location where the wind conditions matched those of the composite fields for each of the three steps of transformation. As the tropical cyclone interacted with the environment, the important structural changes were studied and verified against the observations in Klein et al. (2000) for each step. The main results were that the cloud fields and precipitation patterns developed in a manner very similar to that observed in the Klein et al. (2000) study. Physical processes that were identified in Klein et al. (2000) to be occurring during transformation based on 1° lat./long. NOGAPS analyses were generally verified in the higher-resolution, but idealized COAMPS simulations. In addition, the higher-resolution COAMPS fields allowed investigation of a hypothesis proposed in Klein et al. (2000) that it was interaction with the low-level temperature gradient associated with the baroclinic zone that produced the dry slots in the

clouds, and finally the erosion of the southern eyewall convection of the tropical cyclone. The COAMPS simulations suggest that it is the interaction between the tropical cyclone circulation and upper-level environmental winds that produce deep mechanically forced subsidence into the western and southern portions of the tropical cyclone core (Ritchie and Elsberry 2001). The subsidence not only suppresses convection in that region of the tropical cyclone, but also produces subsidence warming in the middle to low levels of the tropical cyclone. The result is a significant enhancement of the low-level warm core that may be helping to maintain the low-level wind circulation. By the latter stages of transformation, the tropical cyclone is being advected more rapidly by the mean flow, and the subsidence lags the TC core. A second low-level warm anomaly develops just upstream of the tropical cyclone remnants. This second warm anomaly has an associated surface pressure deficit that may have important consequences for the interaction of the tropical cyclone remnants with an upper-level trough and re-intensification as an extratropical cyclone (Ritchie and Elsberry 2001).

These results are extended by adding a realistic upper-level trough into the simulated midlatitude flow. Such upper-level features have been identified with rapid re-intensification of the transformed tropical cyclones into intense midlatitude storms. In the first series of simulations, sensitivity to the initial positions of the tropical cyclone and upper-level feature is explored as in Klein et al. (2001).

Preliminary results indicate a strong sensitivity to the positions where a difference of only a few tens of kilometers may result in no intensification as opposed to deep intensification. Analysis of the results is continuing to determine the source of this sensitivity.

(2) The simplest baroclinic environment within which a tropical cyclone can interact is that of vertical wind shear with no horizontal variation, and thus a constant, weak temperature gradient. The motion and structural development of tropical cyclones in such an environment has been numerically simulated using the PSU/NCAR mesoscale model (Frank and Ritchie 1999; 2001). These studies show that when unidirectional shear is applied to a simulated mature storm, weakening occurs (measured by a rise in the central pressure). Furthermore, the amount of weakening, and the time lag until weakening occurs, is related to the strength of the shear. For a relatively weak shear (e.g.,  $5 \text{ m s}^{-1}$ ), the simulated tropical cyclone continues to slowly intensify until 39 hours after onset of shear when dramatic filling occurs. For a strong shear ( $15 \text{ m s}^{-1}$ ), the weakening is evident immediately upon onset. Probably the most important result of this study was the conclusion that the time lag between onset of shear and subsequent filling was because of internal adjustments that occurred in the tropical cyclone core during the period between onset of shear and filling that gradually eroded the axisymmetric storm structure.

The development of persistent asymmetries in convection in these simulations due to the unidirectional vertical shear were directly responsible for the subsequent vortex breakdown, although the exact details of the processes involved are still under investigation. It is also important to note that in the above simulations, storms were subjected to a wind shear environment for longer time scales than would generally occur in the atmosphere (Frank and Ritchie 2001).

Preliminary calculations indicate that the environmental shear is rarely unidirectional, nor is it uniformly varying through the troposphere. More complicated vertical shear structure may have a more radical effect on the development of convection in the eyewall that appears to be so important for maintaining the tropical cyclone intensity. Preliminary results indicate that the addition of a beta plane results in an additional environmental low-level jet through the core of the tropical cyclone that

appears to modulate the inner-core convection. Asymmetric convection developed in the southeast (downshear left) quadrant as would be expected from the addition of a 5 m/s northwesterly shear due to beta. Early results indicate that for small amounts of additional imposed environmental shear (e.g., 5 m/s easterly shear), it is the beta-forced shear effect that dominates the precipitation patterns. The addition of realistic vertical wind shear structure continues, and we expect to demonstrate important differences in the convective response of the tropical cyclone core to the onset of shear.

(3) Traditionally good data sets of tropical cyclone formation have been limited to special data collection efforts, such as the ONR-sponsored TCM-92 and TCM-93 field experiments. In recent years, the number of remote sensing instruments on satellites has been steadily increasing, and the innovative data available from these platforms is becoming available. This study aims to not only understand the physical processes that differentiate developing from non-developing tropical cyclones, but to do so using technology and data sources that are becoming routinely available to forecasters. At this stage, a non-developing case, and a developing case have been studied in detail (Ritchie et al. 2001). It is intended that the number of cases studied will be extended during the next year.

## SUMMARY

Significant advances have been made in the understanding of how a tropical cyclone interacts with the surrounding environment. Because interaction with the environment affects a tropical cyclone's intensity and structure, it is important to understand these processes in order to predict intensity change of a tropical cyclone.

The intensity changes associated with extratropical transition of a tropical cyclone are particularly difficult to forecast and the knowledge we gain in studying the physical processes associated with the movement of a tropical cyclone to higher latitudes can help to improve forecasts of these phenomena.

New satellite technology has provided an abundance of data sources to forecasters, particularly in the remote tropical oceans where data have been traditionally sparse, and where tropical cyclones form. These data can be difficult to process in the forecast office where timely forecasts must be provided every few hours. Two advantages of this project are: (1) to better understand the physical processes associated with tropical cyclone formation through access to many cases, and (2) to find ways to make more effective use of the wealth of data now available.

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